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MESOSCALE CHARACTERISTICS OF A TOPOGRAPHICALLY MODULATED FRONTAL ZONE OVER NORWAY

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1. INTRODUCTION

During late January 1995, a severe downslope windstorm occurred in the Oppdal Valley of central Norway, which is one of numerous isolated valleys amidst extremely complex topography. High winds destroyed many well-constructed homes and factories that survived the elements for decades. This valley and the village of Oppdal are located to the southwest of Trondheim approximately 80 km from the western coast of Norway, just to the north of the highlands of Jotunheimen and Dovre (Fig. 1). A motivation for this study is that the evolution and dynamics of severe downslope windstorms that occur in complex topography and have origins in orographically-deformed frontal zones, as in this case, remain somewhat of an enigma.

Bjerknes and Solberg (1921) describe the deformation and subsequent fracture of a warm frontal zone as a result of the influence of the complex topography of central Norway. Since this study, numerous observational (e.g., Volkert et al. 1991) and numerical studies (e.g., Bannon 1984) have shown that fronts tend to weaken on the windward sides of mountains and strengthen again on the lee slopes. Warm fronts that contain weak static stability aloft and reverse shear profiles with embedded jets may be conducive for gravity wave amplification, internal hydraulic jumps and severe downslope winds (e.g., Smith 1985; Durran 1990).

2. MODEL DESCRIPTION

The atmospheric portion of the Navy's Coupled Ocean-Atmospheric Mesoscale Prediction System (COAMPS) (Hodur 1993), which solves the fully compressible equations of motion, is used. Physical parameterization schemes applied include: explicit mixed-phase cloud microphysics, subgrid-scale convection, short- and long-wave radiation processes, and planetary boundary-layer mixing using an explicit equation for the turbulent kinetic energy. Four grid meshes are used in this study with horizontal grid increments of 27 km, 9 km, 3 km and 1 km, respectively (Fig. 1). A 24-h simulation is performed from the initialization time of 0000 UTC 31 January 1995. The model initialization is based on optimum interpolation analysis.

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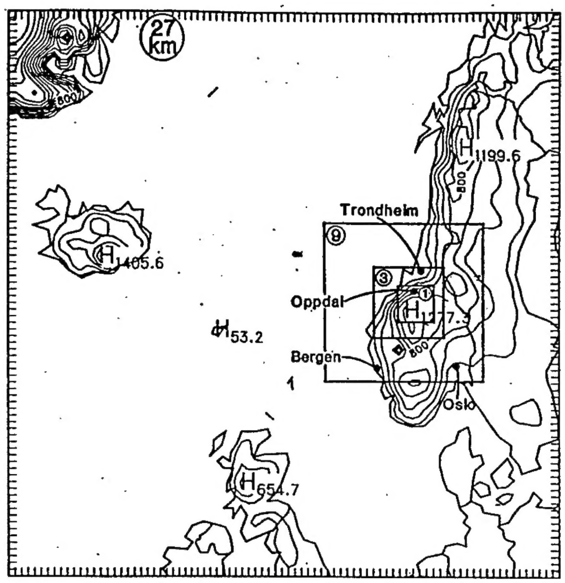

Fig. 1. Terrain field (every 200 m) for the coarse mesh (27 km). The three inner boxes represent the locations of the nested grids with grid increments of 9 km, 3 km and 1 km.

3. FRONTAL-SCALE PERSPECTIVE

At 0000 UTC 31 January 1995 a developing baroclinic wave was located in the Norwegian Sea to the west of Norway with a central pressure of 963 mb. A noteworthy feature of this baroclinic system is a well-defined warm frontal zone. Characteristics of the translating warm front include an intense, prefrontal, low-level, southerly jet with a maximum in excess of 45 m s^{-1} and a significant thermal gradient. The low-level jet is positioned at the base of a nearly-linear sloping frontal inversion centered near 900 mb with strong vertical wind shear above the jet embedded within the frontal zone.

As the synoptic-scale warm front progresses eastward, the steep topography of southern and central Norway begin to distort the frontal zone. By 1200 UTC 31 January (12-h time), the frontal zone has horizontally and vertically wrapped around the central highlands of Norway, in essence similar to that discussed by Bjerknes and Solberg (1921). As the southerly low-level jet ascends the smooth orography of the coarse mesh, a substantial mountain-wave disturbance forms to

the lee of the mountainous region of central Norway in the vicinity of Oppdal on the coarse-mesh grid.

The kinematic frontogenesis equation for virtual potential temperature that includes processes related to deformation, tilting, and differential diabatic heating was computed for the full physics simulation and a simulation without topography. The mesoscale response to the steep topography of central Norway is complex. The warm front is strengthened, especially on the lee side, by topographic deformation associated with the high amplitude mountain wave (Fig. 2a). Contribution by the tilting term leads to an intense region of frontolysis immediately downstream of the strongest region of frontogenesis. This frontogenesis/frontolysis dipole, which is a result of the vertical motion and static stability anomalies associated with the large-amplitude mountain wave, acts to strengthen and deform the warm front in the horizontal, as well as the vertical. The simulation without topography has a quasi-linear frontal structure with locally weaker frontogenesis in central Norway (Fig. 2b). The maximum 850-mb thermal gradient is strengthened by a factor of three through the topographic deformation processes.

3. FINE-SCALE WINDSTORM ASPECTS

Numerous fine-scale mountain waves were excited as the strong southerly flow ascends the mountains of central Norway. The simulated 870-mb wind speed for 1400 UTC 31 January (14 h) for the inner-grid mesh (Δx=1 km), shown in Fig. 3, indicates that, despite the known difficulties in predicting low-level winds in complex terrain, the model simulates the domain-wide maximum wind speed nearly coincident with the region of observed windstorm damage. The wind speed maximum at ~300-m above the valley is 55-60 m s^{-1} and located in the Oppdal Valley to the northeast of Oppdal. Observational estimates indicate that the windstorm occurred at approximately 1500 UTC with wind gusts in excess of 60 m s^{-1} (Harstveit et al. 1995).

A south-north oriented vertical cross section of potential temperature for the 14-h time (1400 UTC 31 January), shown in Fig. 4, indicates that a large-amplitude mountain wave is centered in the Oppdal Valley. The warm-frontal inversion has undergone substantial distortion. An upstream inversion near the mountain top is often associated with downslope windstorm events (Durran 1990). A weak stability region in the 350-500-mb layer may be an indication of a critical layer that acts to reinforce the low-level winds by ducting and reflecting the internal gravity waves. In this case, the mountain wave appears to be confined to the lower troposphere, unlike the full-tropospheric, large-amplitude waves found in other cases (e.g., Lilly 1978). As the mountain wave formed, a well-defined upstream tilt is present and is especially apparent on the outer meshes. The lack of vertical tilt at this time (Fig. 4) suggests that the waves may be trapped. Moreover, the strong stable layer near the surface with weaker stability aloft results in the Scorer parameter decreasing substantially with height, which is a condition often associated with trapped waves. As the wave amplifies and steepens, wave breaking occurs in the lower troposphere as suggested by the nearly adiabatic conditions with near-zero cross-mountain component in the Oppdal Valley at 650 mb (Fig. 4). Additionally, internal hydraulic jump characteristics are present similar to other mountain wave events (e.g., Smith 1987).

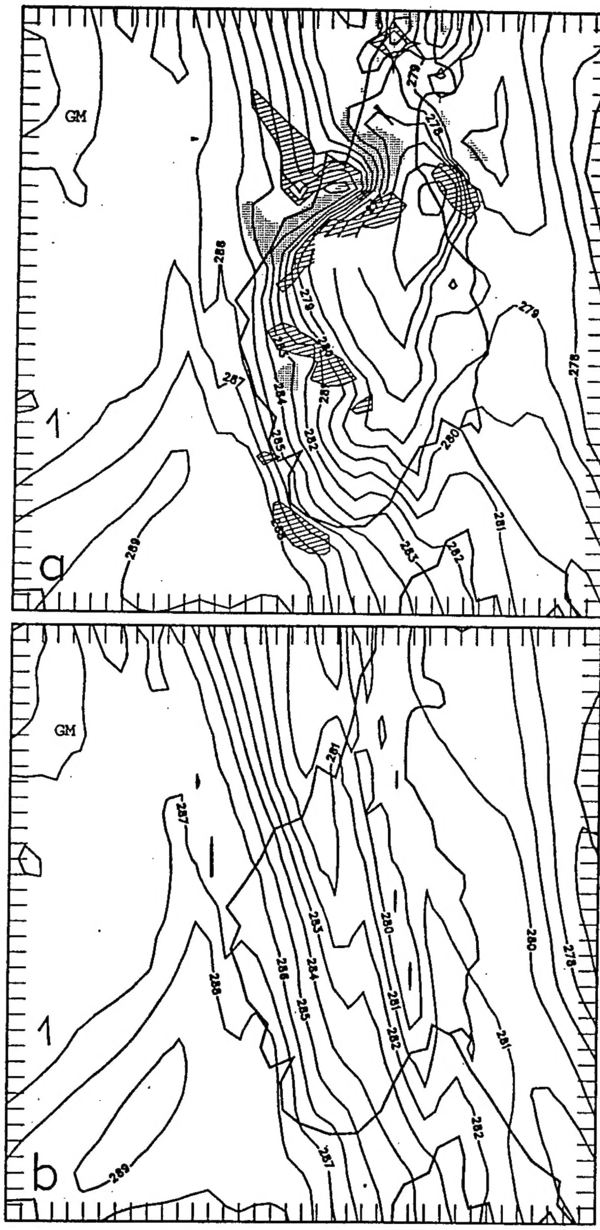

Fig. 2. Sub-domain of the coarse-mesh (27 km) 850-mb potential temperature (K) for 15 h for the (a) full-physics and (b) no-topography simulations. The isotherm interval is 1 K. Frontogenesis greater than 5 K/(10 km 6 h) is delineated by the hatched region and frontolysis greater than 5 K/(10 km 6 h) is shown in the shaded area.

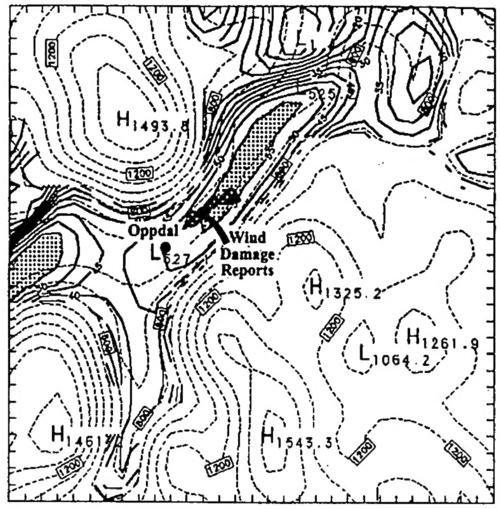

Fig. 3. Sub-domain of the 870-mb winds for the inner mesh (1 km) for 14 h. Light shaded areas correspond to winds in excess of 55 m s^{-1} and dark shading denotes the region of wind damage reports. 870-mb wind speed below the terrain surface (dashed every 100 m) is not displayed.

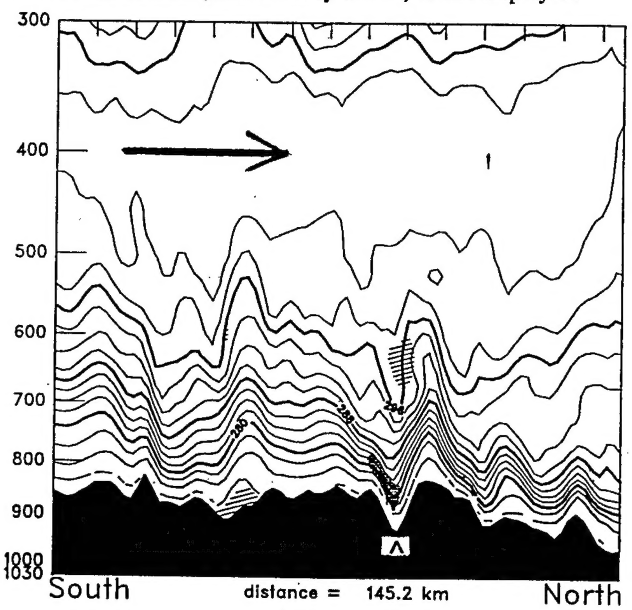

Fig. 4. South-north oriented vertical cross section of potential temperature (K) for 1400 UTC 31 January (14 h) for the inner mesh (1 km). The isentrope interval is 1 K. Cross-mountain wind component in excess of 50 m s^{-1} is shaded. Hatched regions corresponds to cross-mountains speeds less than 5 m s^{-1}. Oppdal Valley shown at the "^".

4. SUMMARY

This study documents a real-data numerical simulation of a severe downslope windstorm event that occurred in central Norway on 31 January 1995 using the Navy's nonhydrostatic mesoscale modeling system. The model successfully captures the development of large near-surface wind speeds in the Oppdal Valley. The coarse-mesh domain results document a warm front and associated low-level jet that evolve from a topographically undisturbed state to a dramatically deformed frontal zone influenced by the high topography of the central highlands of Norway. Marked frontogenesis occurs as a result of strong frontogentical tilting associated with a high-amplitude mountain wave. The Oppdal downslope windstorm formed as a mesoscale response to a low-level jet that was forced over the numerous peaks and valleys that are found in this complex topographic region. Analysis of the model results suggests that the presence of a critical level aloft may have resulted in the trapping and amplification of the internal gravity waves. The results of this study point to a promising future for the simulation of fine-scale structures associated with severe downslope windstorms and topographically-induced flows in both research and operational modes using nonhydrostatic modeling systems, such as the Navy's COAMPS.

5. ACKNOWLEDGMENTS

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